INTEGRATED COOLING DUCT FOR RESIN-ENCAPSULATED DISTRIBUTION TRANSFORMER COILS

Field of the Invention

The present invention relates to the field of electrical transformers, and, more particularly to a dry-type, resin-encapsulated transformer coil having permanently installed cooling ducts that are thermally and electrically compatible with the resin encapsulating the coil.

Background of the Invention

The design and reliability of transformer coils has steadily improved over the last several decades. Today, dry-type encapsulated transformer coils are either coated with resins or cast in epoxy resins using vacuum chambers and gelling ovens. Epoxy provides excellent protection for the transformer coil; however, it can create a problem with heat dissipation. To dissipate the heat from around the coil, cooling ducts are formed at predetermined positions within the coil to aid cooling, improve the operating efficiency of the coil, and extend the operational life of the coil.

The conventional method of creating cooling duct passages is to place solid spacers between successive layers of conductive material during the winding process. Solid metal, cloth-wrapped metal, and greased elastomeric spacers all have been used, as well as shims to create gaps between the layers of the coil. After encapsulating the coil, the spacers then are removed. Regardless of the type of spacers used, the process can result in inefficiencies and the potential for damage, as the spacers must be forcibly removed with pulling devices or overhead cranes. The spacers quite often are damaged while being removed, thus requiring repair or replacement.

Duct spacers, such as aluminum, can also cause damage to the coil in a variety of ways. Stress fractures can form in the coil during the curing process due to the differences in thermal expansion and contraction between the epoxy resin and the aluminum spacers. As mechanical fractures also may be created in the cured coil during removal of the spacers, a minimum spacing requirement between spacers reduces the number of cooling ducts that can be formed in the coil. This in turn creates an incremental increase in the required thickness of the conductive material needed to adequately dissipate heat during operation. Further, chips or blocks of epoxy often break away from the coil while the spacers are being removed, rendering the encapsulated coil useless for its intended purpose.

Summary of the Invention

The present invention is directed to an integrated tubular cooling duct for a dry-type, resin-encapsulated transformer coil, and also to a dry-type, resin-encapsulated transformer coil having permanently installed cooling ducts that are thermally and electrically compatible with the resin encapsulating the coil.

One aspect of the present invention is a tube formed of epoxy resin and adaptable for permanent installation as a cooling duct in a dry-type, resin-encapsulated transformer coil. The tube may be formed as a resin-coated, fiberglass matrix, which is pultruded and cured to a flexible, but durable tube. The cured tube has a thermal gradient that is similar to the thermal gradient of the epoxy resin that is used to subsequently encapsulate the transformer coil. Thus, the materials expand and contract at approximately equal rates, thereby reducing internal stresses that are inherent in epoxy resin curing cycles. One or more of the pultruded tubes are cut to length for installation between the windings of the coils. The tubes are cut slightly shorter than the winding height of the coil to eliminate interference with the operators during the winding process.

In a preferred embodiment of the present invention, the cooling duct tubes are permanently installed in a dry-type, resin-encapsulated transformer coil. The encapsulated transformer coil comprises a coil having a plurality of layers formed from a continuous length of conductive material, and multiple cooling ducts that are formed as described above and spaced between the wound layers of conductive material. A resin encapsulates the coil and surrounds each of the cooling ducts. The cooling ducts and the resin encapsulated coil are thermally and electrically compatible.

The present invention also includes a method of manufacturing a transformer coil encapsulated in a casting resin, with integrated resinous cooling ducts. A disposable inner mold is placed over an annular form, or support, on a mandrel shaft. A continuous coil of conductive material then is wound around the inner mold, while the pre-cut cooling ducts are interspaced between successive layers of the coil. At the completion of the winding, the coil is removed from the winding machine mandrel and uprighted on a silicone base mat to seal the lower end of the assembly, preventing epoxy leakage during the subsequent encapsulation process. The mold is filled with epoxy resin to encapsulate the coil and encase the cooling ducts. The assembly then is cured in a curing oven, after which the inner and outer molds are removed.

These and other aspects of the present invention will become apparent to those skilled in the art after a reading of the following description of the preferred embodiments when considered in conjunction with the drawings. It should be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention as claimed.

Brief Description of the Drawings

Figure 1 is a perspective view of the resin cooling duct of the present invention;

Figure 2 is a perspective view of a dry-type, resin-encapsulated transformer coil with permanently installed resin cooling ducts;

Figure 3 is a cross-sectional view of the transformer coil of Figure 2, taken along Line 3—3;

Figure 4 is a perspective view illustrating the steps of winding a length of conductive material to form a coil, and positioning a plurality of resin cooling ducts between layers of conductive material;

Figure 5A is a perspective side view of the plugs for temporary installation in the ends of the resin cooling ducts of the present invention;

Figure 5B is an end view of the plugs of Figure 5A; and

Figure 6 is a perspective, cut-away, view illustrating the steps of placing the outer mold around the coil and filling the volume between the inner and outer molds with a resin.

Detailed Description of the Preferred Embodiments

As shown in Figure 1, one aspect of the present invention is directed to a tube 10, for permanent installation as a cooling duct in a resin-encapsulated transformer coil. The tube has a cross-section that is generally elliptical, with rounded ends 12 and substantially straight sides 14. While the precise geometry of the tube is not critical to the present invention, it has been found that, when the linear dimension, x, of the tube is about three times the width, d, of the tube, the tube is optimally shaped for placement between the alternating layers of a wound coil. With these relative dimensions, the tube is also structurally optimized, and provides optimal heat transfer from resin-encapsulated systems, such as transformer coils. By way of example, one tube constructed according to the present invention has a linear dimension, x, of about 2.7 inches, a width, d, of about 0.9 inches, and a wall thickness, w, of about 0.1 inches. As will be described in greater detail below, the tube is designed to withstand a vacuum of at least one millibar during a vacuum casting procedure.

The tube of the present invention preferably is formed from a suitable thermoplastic material, such as a polyester resin, in a pultrusion manufacture. Pultrusion is a process for producing a continuous length of a fiber-reinforced polymer profiled shape, such as a tube or cylinder, in which coated fibers are drawn through a heated die to produce a high strength shape. An example of the polyester resin used to form the tube is E1586 Polyglas M, available from Resolite of Zelienople, Pennsylvania. The pultruded tube is reinforced with fiberglass filaments aligned as either unidirectional roving or a multi-directional mat. The reinforcing configuration used in the tube of the present invention includes an outer fiberglass reinforcing mat and an inner fiberglass reinforcing mat. The tube, once formed, is cured beyond B-stage by any of the conventional methods known in the art for such curing. For integration into a dry-type, encapsulated transformer coil, certain material properties are required. The tube described herein, when tested in accordance with ASTM D-638, "Standard Test Method for Tensile Properties of Plastics," has an ultimate tensile strength of about 30,000 psi longitudinally, 6,500 psi transverse; an ultimate compressive strength of about 30,000 psi longitudinally, 10,000 psi transverse per ASTM D-695, "Standard Test Method for Compressive Properties of Rigid Plastics", and, an ultimate flexural strength, when tested in accordance with ASTM D-790, "Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials" of about 30,000 psi longitudinally, 10,000 psi transverse. The modulus of elasticity is approximately 2.5E6 psi longitudinally per ASTM D-149, Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies." Electrically, the tube has an electrical strength short time (in oil), per ASTM D-149, of about 200 V/mil (perpendicular) and 35 kV/inch (parallel). Preferably, the thermal conductivity of the tube is at least about 4 Btu/(hr*ft^2*°F/in).

The length, l, of the tube is entirely dependent upon the application; i.e., the pultruded tube is cut to length for the particular transformer application. As explained in greater detail below, the overall length of the tube will be less than the overall height of the wound transformer coil, so that the tube is completely encased, with the end edges of the tube bound to the cured resin. In a preferred embodiment of the present invention, the tube described above is permanently installed in a dry-type, resin-encapsulated transformer coil.

Referring to Figures 2 and 3, the dry-type, resin-encapsulated transformer coil 20 comprises a coil 22, a plurality of integrated cooling ducts 24, and a resin 26 encapsulating the coil 22. When formed, the body of the transformer coil 20 is defined between inner surface 20a and outer surface 20b, both shaped by molds, as described below. The inner

surface 20a circumferentially defines an open area or core 21, formed as described in greater detail below. The coil 22, as wound about the core 21, consists of alternating layers of conductor sheeting 22a and insulating sheeting 22b. As the conductor sheeting 22a and insulating sheeting 22b are continuously wound about the core 21, cooling ducts 24, formed as the tubes described above, are inserted and interspaced between successive layers. The cooling ducts of the present invention are permanently incorporated into the encapsulated transformer coil. The addition of integrated cooling ducts 24 improves the dielectric strength of the coil. As used herein, and as generally defined in the industry, "dielectric strength" refers to the maximum electrical potential gradient that a material can withstand without rupture. Not only do the integrated cooling ducts 24 have desirable dielectric characteristics, but also they add an additional dielectric barrier to the wound coil 22. This increases the durability and service longevity of the coil 22. As these integrated cooling ducts 24 of resin construction also increase the cooling capacity of each layer of coil 22, the thickness of conductor 22a required for optimal performance may be decreased. For example, the thickness of the conductor sheeting 22b may vary from about 0.020 inches to 0.180 inches, with the spacing between integrated ducts ranging from about 0.125 inches to 1.0 inches. Therefore, since resin breakage due to duct bar or spacer removal is not a concern with the integrated cooling duct construction, the integrated ducts 24 also may be placed more closely together, permitting the total number of cooling ducts 24 to increase, with a proportional increase in cooling capacity. As the number of integrated ducts increases, the required thickness of the conductor 22a decreases.

The wound transformer coil 20 is encapsulated by an epoxy resin 26 that is poured in the volume between inner and outer molds. The encapsulating resin is available from Bakelite AG of Iserlohn, Gemany as Rutapox VE-4883. This thermosetting resin is electrically and thermally compatible with the polyester resin construction of the cooling ducts 24. Once encapsulated and cured, the construction of the transformer coil is complete.

The present invention also provides a method of manufacturing a transformer coil encapsulated in a casting resin. While there are several manufacturing methods for constructing the dry-type, resin-encapsulated transformer coil of the present invention, one method is to utilize a disposable wrap and band mold with an integrated winding mandrel. This method, as will be only summarized herein, is described in U.S. Patent No. 6,221,297 to *Lanoue et al.*, the content of which is incorporated herein in its entirety.

As shown in Figure 4, a coil winding machine 40, having a conventional mandrel 41, is used to produce a coil 20, having a substantially circular shape. Once an inner mold 42 of

sheet metal or other suitable material is mounted on the mandrel 41 to form the core, it is ready to have the coil wound thereon. The inner mold 42 typically is first wrapped with a glass grid insulation (not shown), followed by a first winding, or layer, of the coil 22. As best seen in Figure 4, the coil 22 is wound from alternate layers of copper conductor sheeting 22a and insulating sheeting 22b. The thickness of the insulation sheeting is also dependent upon the particular transformer coil configuration, but in embodiments constructed according the the present invention, may vary from between about 0.005 inches and 0.030 inches. During the winding process, the cooling ducts 24 are inserted between layers of conductor 22a to provide cooling ducts in the completed transformer. As will be appreciated, the integrated cooling ducts 24 may be inserted between each layer of conductor 22a, between alternating layers, etc., again dependent upon the particular transformer coil construction.

Duct plugs 25, 27, which may be installed at any time prior to resin encapsulation of the coil 22, are inserted into the open ends of cooling ducts 24 to keep resin from flowing into ducts 24 during the resin encapsulation. Figures 5A and 5B illustrate in an environmental view the relative placement and geometry of the plugs 25, 27. The top plug 25 is dimensioned to frictionally fit within the top opening of a cooling duct 24. As used herein, the "top" of the cooling duct is on that end of the coil from which the coil leads (not shown) extend. The top plug 25 is tapered inward (i.e., downward), and has ribs 25a around its periphery to ensure a positive seal with the inner surface of the cooling duct 24. The outer (i.e., upward) body 25b of the plug is tapered outward slightly so that it can be easily removed from the surrounding cured resin following encapsulation. A handle or gripping portion 25c facilitates removal after the curing process. Because the plugs 25, 27 will seal each end of each cooling duct 24 during the resin encapsulation and curing process, an open passage or relief vent 25d is formed through plug 25 to prevent collapse of the cooling duct 24. A bottom plug 27 performs the same function as the top plug, except that a vacuum relief is not required and a handle is not needed. Bottom plug 27 also has ribs 27a for frictional engagement with the inner walls of the cooling duct 24. The outermost end 27b of plug 27 is substantially flat so that the coil may be uprighted and seated with the bottom end on a mat for the subsequent resin encapsulation.

Following the winding of the coil 22 into the desired number of layers, and having placed a sufficient number of cooling ducts 24 between the layers, the coil is removed from the winding machine 40 and uprighted with the top plugs facing upward. The coil 20 is placed on a mat 50 of silicone or other suitable material that may be compressed. When so placed, the flat ends 27b of bottom plugs 27 will be pressed against the mat 50. The outer

mold then is ready to be wrapped around the uprighted coil 20. As best seen in Figure 6, an outer mold 60 surrounds coil 20. Outer mold 60 is formed of a sheet metal or other rigid material that is fastened, or banded around coil 20, leaving a gap between the mold 60 and the coil 20 so that encapsulation will be total. *Lanoue et al.* discloses one construction for the outer mold, but other suitable forms of molds well known in the art may be used. Compression of the outer mold 60 against the silicone mat 50 will prevent epoxy leaks from the bottom of the coil during the encapsulation process.

With the outer mold 60 in place, the epoxy encapsulation may proceed. A flowing epoxy resin 26 is poured into the mold to encapsulate the coil, and to encase the spaced cooling ducts 24. When poured, the epoxy resin 26 settling into the lower spaces between the inner and outer molds will surround bottom plugs 27 to a depth substantially even with the flat portions 27b of plugs 27. The resin will be poured until it extends about 3/16 inches above the top edges of the cooling duct 24 upper ends.

The curing process is conventional and well known in the art. For example, the cure cycle may comprise a (1) gel portion for about 5 hours at about 85 degrees C., (2) a ramp up portion for about 2 hours where the temperature increases from about 85 degrees C. to about 140 degrees C., (3) a cure portion for about 6 hours at about 140 degrees C., and (4) a ramp down portion for about 4 hours to about 80 degrees C. Following curing, the inner and outer molds are removed. The top plugs 25 may be easily removed with pliers or other gripping devices without damaging the surrounding resin. The bottom plugs may be removed by inserting a bar or rod (not shown) through the top end of each cooling duct and punching out the bottom plugs.

Although the present invention has been described with preferred embodiments, it is to be understood that modifications and variations may be utilized without departing from the spirit and scope of the invention, as those skilled in the art will readily understand. Such modifications and variations are considered to be within the purview and scope of the appended claims and their equivalents.